

Article

Contrasting Shallow Soil-Moisture Dynamics Between Microtopographic and Flat Reclamation Areas in a Cold-Arid Abandoned Quarry: A One-Year Field Case Study

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Abstract

Water scarcity strongly constrains the revegetation of disturbed mine substrates in cold-arid regions. This study compared soil-moisture dynamics between a microtopographic reclamation area and an adjacent flat reclamation area in an abandoned stone quarry within the Kalamaili Ungulate Nature Reserve, northwestern China. The integrated restoration treatment, established in 2018, combined linear trenches 30–40 cm deep and spaced 60 cm apart, native seed sowing, transferred seed-bank topsoil, and water-retaining material. From January to December 2024, sensor-derived apparent volumetric water content was monitored at five depths—0–10, 10–20, 20–30, 30–40, and 40–50 cm—at 10 min intervals using sensors operated with the manufacturer’s standard calibration. Following quality control and temporal synchronization, 41,475 valid timestamps were retained for each monitored profile. The study provides a continuous full-year, multi-depth record from an unirrigated, cold-arid reconstructed quarry substrate, a setting that remains underrepresented in previous micro-catchment and dryland-restoration research. However, this study is based on a single hydrological year and does not directly measure plant physiological responses or long-term restoration outcomes. Therefore, elevated soil moisture should be interpreted as a preliminary indicator of restoration potential rather than a definitive measure of ecological recovery success. The monitored microtopographic profile maintained higher mean apparent water content than the flat profile during most of the year. The largest annual relative profile difference occurred at 10–20 cm depth, reaching 18.0%, followed by 11.7% at 0–10 cm, whereas differences decreased below 20 cm and reached 1.9% at 40–50 cm. During selected rainfall and probable snowmelt periods, the microtopographic profile exhibited larger wetting responses and slower post-event recession. These patterns indicate contrasting upper-profile wetting and drying dynamics between the two monitored reclamation configurations. However, runoff, infiltration, evaporation, snow accumulation, soil-water potential, and vegetation responses were not measured directly. Moreover, monitoring began several years after vegetation establishment, and trenching, seed addition, seed-bank transfer, and water-retaining material were not evaluated independently. The findings should therefore be interpreted as a site-specific post-establishment comparison rather than evidence of the isolated effect of microtopography. Replicated, multi-year studies are required to determine the mechanisms, effectiveness, and broader transferability of this integrated reclamation configuration.



Academic Editor: Youjin Yan

Received: 22 June 2026

Revised: 29 July 2026

Accepted: 31 July 2026

Published: 5 August 2026

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Keywords: micro-catchment water harvesting; soil-water retention; mine-land reclamation; cold desert; revegetation

1. Introduction

Mining disturbance can severely alter landform, substrate structure, vegetation, and hydrological functioning, particularly in arid and semi-arid regions where ecological recovery is constrained by limited precipitation and high atmospheric water demand [1,2]. At the Ouluo abandoned quarry in northwestern China, mean annual precipitation is approximately 50–80 mm, groundwater occurs at a depth greater than 200 m, and external irrigation is prohibited within the protected nature reserve. Quarry excavation and backfilling also replaced the original soil profile with a heterogeneous reconstructed substrate [3]. These conditions create a severe mismatch between short-lived rainfall or snowmelt inputs and the sustained near-surface water availability required for vegetation establishment.

Micro-catchments, contour trenches, furrow–ridge systems, and other terrain modifications have previously been used to redistribute limited water in drylands [4,5]. Their hydrological performance, however, depends on precipitation form, soil or substrate texture, compaction, surface roughness, vegetation, and construction geometry. Studies from the Negev Desert primarily concern rainfall-generated runoff, whereas research on the Loess Plateau commonly involves deeper loess profiles, greater annual precipitation, agricultural land, or established vegetation. These environmental settings differ substantially from a cold-arid quarry where winter snowfall, frozen-soil conditions, reconstructed sub-surface material, and an inaccessible water table may influence soil-water dynamics [6–8]. In addition to surface roughness, soil physical properties—such as bulk density, texture, and infiltration capacity—are severely altered by mining activities and strongly modulate water retention and percolation. These properties interact with micro-topography, and their characterization is essential for understanding why trenching enhances moisture more effectively than leveling.

Recent studies have further shown that soil moisture in semi-arid mining landscapes is spatially heterogeneous and responds jointly to mining disturbance, substrate conditions, topography, climate, and vegetation development [9,10]. Recent rainwater-harvesting research has also demonstrated that conclusions regarding runoff, infiltration, or plant performance require replicated controls and direct hydrological or vegetation measurements [11,12]. Moreover, precipitation in this hyper-arid region is not only scarce but also highly variable inter-annually, with frequent multi-year droughts that further hinder natural regeneration and amplify the need for water-harvesting interventions. These studies underline the need to distinguish observed soil-moisture differences from the processes presumed to cause them.

The novelty of the present study does not lie in proposing microtopographic water harvesting as a new concept [13–15]. Rather, it lies in the continuous full-year monitoring of two contrasting post-establishment reclamation profiles at 10 min resolution and at five depths from 0 to 50 cm under extremely water-limited, cold-arid quarry conditions [15–21]. The dataset permits evaluation of vertical moisture differences and event-scale wetting and recession during rainfall and probable snowmelt periods [22–24]. Unlike many previous studies, the intervention received no external irrigation. Nevertheless, because trenching was combined with native seed sowing, transferred seed-bank topsoil and litter, and water-retaining material, the study evaluates an integrated reclamation configuration rather than the isolated effect of microtopography [25,26].

The restoration intervention was initiated in 2018 and included four closely associated components: surface leveling, construction of linear trenches, sowing of locally collected native seeds, transfer of seed-bank topsoil and litter, and placement of water-retaining material in trenches or planting holes. Visual observations during 2020–2022 indicated greater vegetation development in the restored microtopographic area than in adjacent leveled areas. However, because these measures were implemented as an integrated restoration package, their individual contributions could not be separated.

Continuous soil-moisture monitoring began after the restoration area had already undergone several years of vegetation development. Consequently, the 2024 measurements cannot reconstruct the hydrological conditions that controlled germination and early community development during 2018–2020. The observed soil-moisture differences may reflect not only the original surface configuration but also subsequent vegetation–soil feedbacks, including root development, altered substrate structure, shading, and plant water uptake. Given that similar abandoned mining lands with comparable aridity and groundwater constraints exist across Central Asia, the Middle East, North Africa, and Australia, the passive trenching approach, if validated, can serve as a low-cost, transferable restoration model for regions where irrigation is unavailable or prohibited.

The objective of this study was therefore to compare soil-moisture dynamics during one post-establishment year between monitored microtopographic and flat reclamation profiles. Specifically, we aimed to: (1) describe annual soil-moisture dynamics at five depths from 0 to 50 cm; (2) quantify relative differences in mean soil moisture between the monitored profiles; (3) compare their responses during selected rainfall and snowmelt periods; and (4) evaluate the potential implications and limitations of these patterns for cold-arid mine-land revegetation. Because the study was conducted at one site over one year, it is treated as a field case study rather than a spatially replicated test of a universally applicable restoration design.

Based on the intended water-concentrating function of the constructed trenches, we hypothesized that, during the 2024 monitoring year, the microtopographic profile would exhibit: (H1) higher annual mean apparent soil-water content than the flat profile, with the largest difference occurring in the upper 0–20 cm; and (H2) larger event-related moisture increases and slower post-event recession following rainfall or spring snowmelt. These hypotheses apply to the two monitored post-establishment reclamation profiles and do not isolate trenching from the accompanying seed-bank transfer, native seed sowing, water-retaining material, vegetation development, or substrate differences.

2. Materials and Methods

2.1. Overview of Experimental Area

The study area is located in the Ouluo abandoned stone quarry mining area, which lies within the Kalamaili Ungulate Nature Reserve in Fuyun County, Altay Prefecture, North-western China, at an elevation of approximately 1100 m above sea level. The Kalamaili Mountain Ungulate Nature Reserve is a natural gene pool for wild flora and fauna [3,27] (Figure 1).

The study was conducted in an abandoned stone quarry in which excavation, back-filling, and mechanical disturbance had substantially removed or mixed the original soil horizons. Mining operations brought material from approximately 7–8 m below the former land surface to the surface, producing a heterogeneous reconstructed quarry substrate containing abundant coarse fragments, fine-earth material, compacted zones, and locally developed surface crusts. Because the original pedogenic horizons were no longer intact, the monitored material is referred to as a reconstructed quarry substrate rather than an undisturbed natural soil profile. To ensure comparability between the micro-terrain and

flat control plots, we measured selected soil physical properties—including bulk density, particle-size distribution (sand, silt, clay), and field infiltration rate—at both sites prior to trenching. These initial properties showed no significant differences between the two areas, confirming that subsequent moisture contrasts can be attributed primarily to the micro-topographic treatment rather than pre-existing pedological heterogeneity.

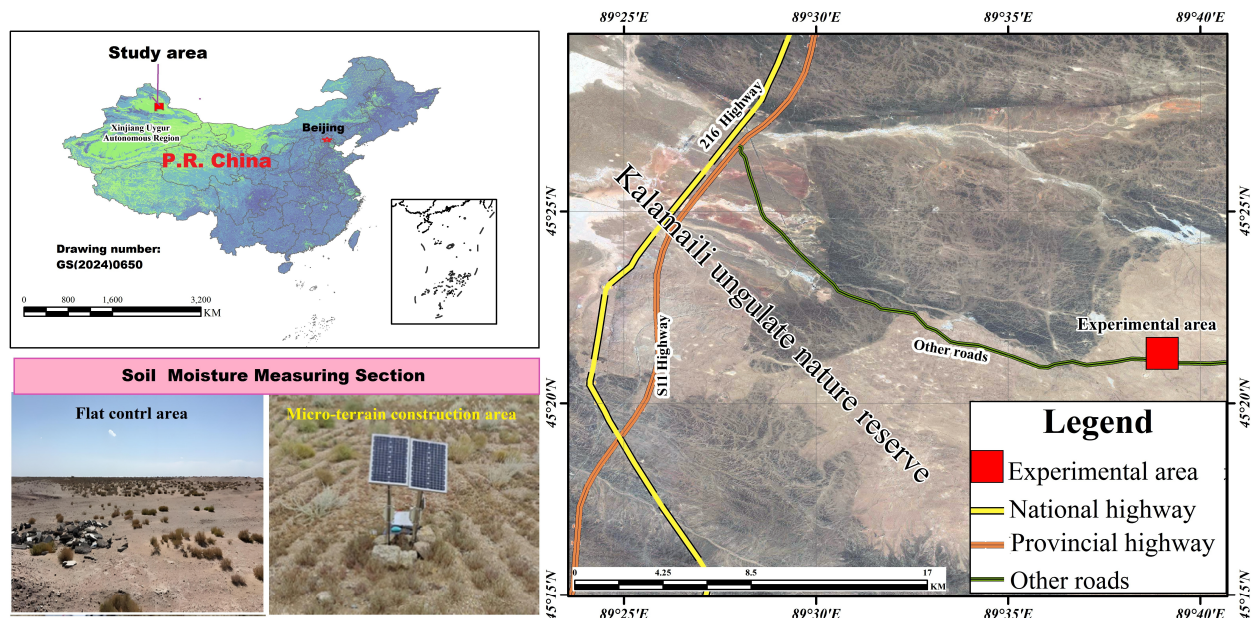


Figure 1. Location and surrounding environment of study area.

The regional climate is strongly continental and cold-arid. Mean annual precipitation is approximately 50–80 mm and occurs as both winter snowfall and warm-season rainfall. Groundwater is deeper than 200 m and is not considered a direct source of water for the monitored 0–50 cm profile. Daily meteorological conditions during the 2024 monitoring period. Groundwater occurs at a depth greater than 200 m and is not considered a direct source of water for the monitored 0–50 cm profile.

It holds significant value for biodiversity conservation in arid regions, ecological research, and scientific exploration [28]. Over the past decade, large-scale mining activities and illegal ore extraction have increasingly devastated the ecological environment of the reserve, leading to a sharp reduction in suitable habitats for wildlife [29,30]. We acknowledge that the experimental design includes only one treated plot and one control plot without true replication, which limits the statistical generalizability of our findings. The trench spacing (60 cm) and depth (30–40 cm) were selected empirically based on previous dryland restoration practices and field observations of natural banded vegetation patterns, rather than from systematic optimization experiments. Future studies should incorporate replicated plots and factorial designs to validate and optimize these parameters. The major ecological and environmental problems include destruction of topography and geomorphology, degradation of soil structure, loss of vegetation, and land desertification. Major ecological and environmental problems caused by mining activities are illustrated in Figure 2.

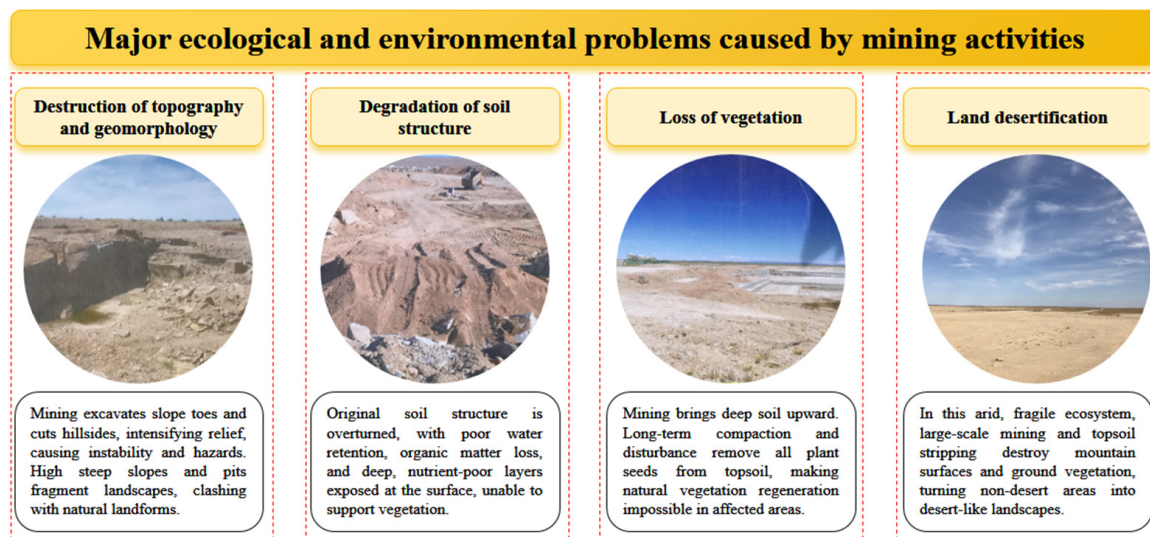


Figure 2. Major ecological and environmental problems caused by mining activities.

2.2. Reconstructed Substrate Characteristics and Data Limitations

Quarry excavation and backfilling substantially disturbed the original soil profile and deposited material from approximately 7–8 m below the former surface at the ground surface. Field observations indicated a heterogeneous reconstructed substrate containing coarse fragments, compacted fine-earth material, and localized surface crusting. However, systematic measurements of particle-size distribution, bulk density, porosity, organic matter, pH, and saturated hydraulic conductivity were not collected as part of the original monitoring program. Consequently, the physicochemical equivalence of the two monitoring locations cannot be fully demonstrated, and differences in reconstructed-substrate properties remain a potential contributor to the observed soil-moisture patterns.

2.3. Overview of the Team's Micro-Topography Restoration Trial

Field surveys conducted before restoration showed that disturbed quarry surfaces treated only by terrain leveling and backfilling remained largely unvegetated after two or more years. Mining had excavated material from approximately 7–8 m below the original surface and deposited it at the ground surface. We acknowledge that site-specific sensor calibration was not performed; instead, we relied on the manufacturer's factory calibration, which may introduce some bias in absolute volumetric water content values, though relative differences between treatments remain reliable. Regarding winter conditions, the sensors operated continuously through sub-zero temperatures; we visually inspected all wintertime data for abnormal spikes or flatlining indicative of freeze–thaw interference, and found no such artifacts, suggesting that frost effects on measurement stability were minimal during the monitoring period. This reconstructed substrate was nutrient-poor, lacked an intact topsoil seed bank, and exhibited limited biological activity, thereby creating unfavorable conditions for the establishment of spontaneous vegetation [30–32]. These constraints were compounded by the regional annual precipitation of only 50–80 mm, a groundwater table deeper than 200 m, and the prohibition of groundwater extraction within the protected nature reserve.

In 2018, an integrated ecological-restoration treatment was implemented across approximately 10.78 ha of disturbed land in the Kalamaili Ungulate Nature Reserve. The restoration treatment combined surface leveling, construction of linear trenches, sowing of locally collected native seeds, transfer of topsoil and surface litter containing a natural seed bank, and placement of water-retaining material within trenches or planting holes. No

irrigation, mulching, groundwater extraction, or other external water supplementation was applied during or after restoration [33]. In this study, “unirrigated” means that no external water was applied to the site. It does not mean that microtopography was the only water-management intervention, because water-retaining material was also placed locally within trenches or planting holes and may have affected the subsequent soil-moisture dynamics.

2.3.1. Restoration Measures and Microtopographic Configuration

The disturbed surface was first leveled to facilitate the construction of a regular microtopographic pattern. Parallel linear trenches were then constructed across the restoration area. The trenches were 30–40 cm deep and spaced 60 cm apart. These dimensions were selected empirically during field implementation rather than through a formal optimization or sensitivity experiment. Therefore, the 30–40 cm depth and 60 cm spacing represent the configuration used at this study site and should not be interpreted as universally optimal dimensions for mine-land reclamation.

The trenches were designed to create local depressions capable of receiving wind-redistributed snow during winter and rainfall during the warm season. Snow accumulated within the depressions was expected to melt during spring and provide a localized soil-water input. However, trench storage capacity, contributing catchment area, snow depth, snow-water equivalent, surface runoff, and infiltration rate were not measured directly. The proposed water-harvesting function should therefore be regarded as the design rationale for the intervention rather than as an independently quantified hydrological process.

Seeds of native plant species were collected from the surrounding natural vegetation and broadcast directly into the constructed trenches. Topsoil and surface litter were also transferred from nearby undisturbed areas to introduce a locally adapted soil seed bank. The species composition, seed viability, sowing rate, and amount of transferred seed-bank material were not quantified as part of the present soil-moisture investigation. These factors may have influenced vegetation establishment and should be considered when interpreting the restoration outcome.

During planting, moisture-holding material was placed at the bottom of the trenches or planting holes to increase local water storage around the establishment zone. The composition and application rate of this material were not evaluated independently in the present experiment. Consequently, any observed difference between the restored and comparison areas may reflect the combined effects of microtopographic modification, transferred seed-bank material, native seed sowing, moisture-holding material, vegetation development, and subsequent soil–plant feedbacks.

2.3.2. Comparison Area and Scope of Treatment Attribution

An adjacent leveled and backfilled area without constructed linear trenches was selected as the flat comparison area. It represented the conventional reclamation condition in which the disturbed surface was smoothed, but no water-harvesting trench–ridge microtopography was created. Both areas remained completely unirrigated [34,35]. The two monitoring profiles were located within the same abandoned quarry and were exposed to the same regional meteorological conditions. The flat profile was selected as close as practicable to the microtopographic profile while avoiding the constructed trench–ridge surface. Both locations had experienced quarry excavation and backfilling. Nevertheless, because the study was not established as a randomized and replicated experiment, exact equivalence in substrate texture, density, salinity, vegetation cover, slope position, and antecedent disturbance cannot be guaranteed. The comparison therefore represents two contrasting existing reclamation configurations rather than fully interchangeable experimental plots.

The microtopographic area and the flat area were not established as a fully replicated factorial experiment. In particular, trenching, native seed sowing, transferred seed-bank topsoil, and moisture-holding material were not tested as separate treatment factors [36,37]. The present comparison therefore evaluates the soil-moisture conditions associated with two contrasting reclamation configurations rather than the isolated effect of trenching alone.

Furthermore, soil-moisture monitoring began several years after implementation of the restoration treatment and after vegetation had already become established. By the 2024 monitoring period, root development, plant water uptake, litter accumulation, shading, and biologically induced changes in substrate structure may have affected the measured soil-moisture dynamics [38]. Accordingly, the 2024 observations represent a post-establishment comparison between the monitored microtopographic and flat areas and cannot reconstruct the hydrological conditions responsible for initial germination and vegetation development between 2018 and 2020. Qualitative field photographs documenting the appearance of the integrated restoration area at establishment and during subsequent site visits are presented in Figure 3. These photographs were not used to quantify vegetation recovery.

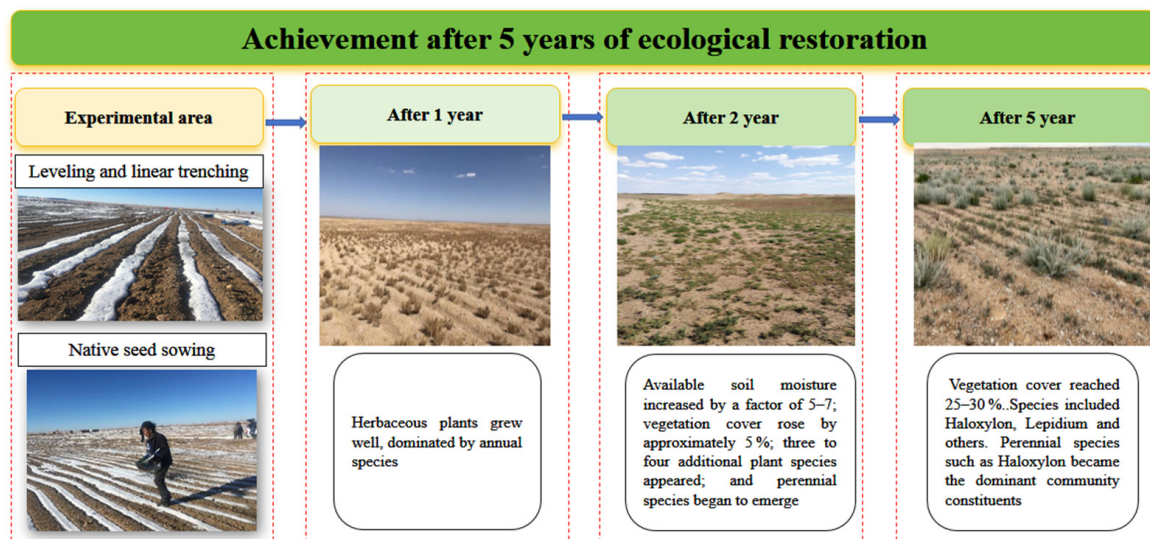


Figure 3. Qualitative photographic record of the integrated restoration area at treatment establishment and during subsequent site visits. The photographs illustrate changes in site appearance but were not used as quantitative measurements of vegetation cover, biomass, survival, species richness, community composition, or physiological condition.

2.4. Soil-Moisture Monitoring Design and Data Quality Control

Soil moisture was monitored using a DJ-6292B soil moisture, temperature, and electrical-conductivity monitoring system supplied by Dianjiang Technology, Shanghai, China. The monitoring system consisted of soil sensors, a DJ-6095 data logger, a solar-power system, and a wireless data-transmission unit. The DJ-6292B system supports multi-depth monitoring of soil moisture, temperature, and electrical conductivity, whereas the DJ-6095 logger supports SDI-12 and serial sensor interfaces. The archived installation records identified the monitoring system and data logger but did not contain sufficient information to verify the exact sensing-probe model or its probe-specific factory accuracy. We therefore do not report unverified technical specifications. The monitoring-system identification, installation configuration, temporal resolution, data completeness, and calibration limitation are reported transparently, and the measurements are interpreted as sensor-derived apparent volumetric water content.

A total of ten sensors were installed in two vertical monitoring profiles. One profile containing five sensors was located in the microtopographic reclamation area, and one

profile containing five sensors was located in the adjacent flat reclamation area. In the microtopographic area, the profile was positioned below the floor of a representative linear trench. In the flat area, the sensors were installed below the local leveled ground surface. The sensing elements were centered at depths of 5, 15, 25, 35, and 45 cm, representing the nominal depth intervals of 0–10, 10–20, 20–30, 30–40, and 40–50 cm, respectively.

The sensors were installed horizontally into a freshly exposed vertical profile face to promote close contact between the probe and the surrounding reconstructed substrate. The access face was subsequently backfilled using the excavated material and gently compacted to reduce preferential water movement along the installation surface. The same depth arrangement and installation procedure were used in the two monitoring profiles. The trench geometry and sensor positions are shown in Figure 4.

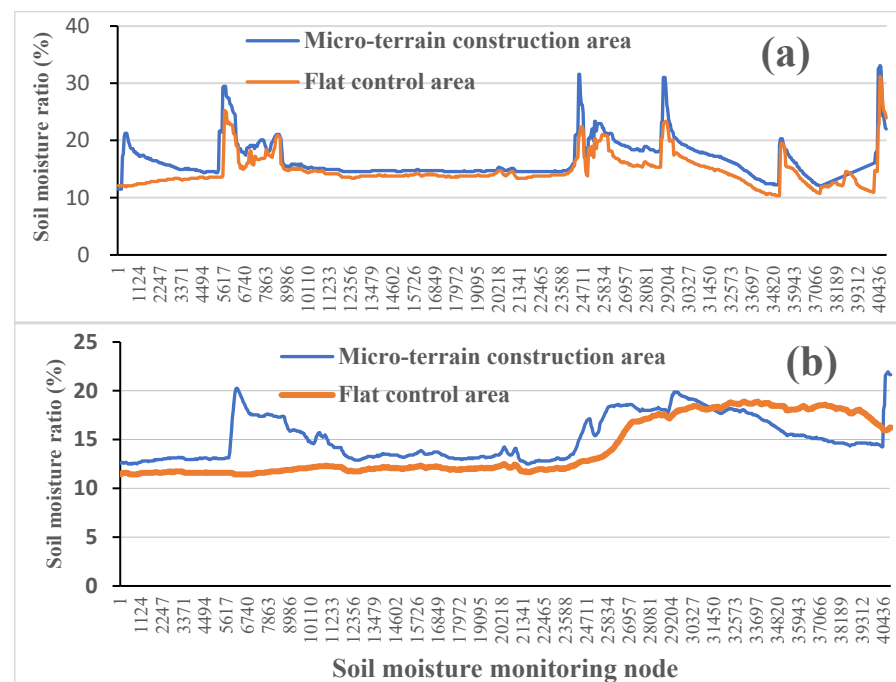


Figure 4. Cross-section of the trench–ridge configuration and soil-moisture monitoring layout. (a) Soil moisture ratio at 0–10 cm depth; (b) Soil moisture ratio at 20–30 cm depth. The figure shows trench depth and width, ridge dimensions, the definition of the 60 cm spacing, slope direction, sensor orientation, monitoring depths, and the position of each monitoring profile relative to the trench bottom, sidewall, and ridge. All comparisons between the micro-terrain and flat control areas are based on a single treated plot and a single control plot without spatial replication. Consequently, the observed annual moisture differences cannot be tested for statistical significance, and the reported enrichment rates should be interpreted as observed trends rather than statistically confirmed treatment effects.

Monitoring commenced in July 2023. Records from July to December 2023 were used for system commissioning and preliminary inspection, whereas the formal study period extended from 1 January to 31 December 2024. Continuous recording at 10 min intervals during the 366 days of 2024 produced a theoretical maximum of 52,704 timestamps per sensor. Following removal of missing records, logger error codes, physically impossible values, and incomplete timestamps, 41,475 synchronized timestamps were retained for each profile, corresponding to a temporal completeness of 78.7%. Because each profile contained five sensors, the retained dataset included 207,375 depth-specific observations per profile. Missing values were excluded and were not interpolated.

The monitoring design provided high temporal resolution but did not provide spatial treatment replication. The 41,475 timestamps were repeated observations from the same two profiles and were not considered independent experimental replicates. Accordingly,

the analysis characterizes temporal differences between the monitored profiles and does not provide a replicated treatment estimate for the complete 10.78-ha site. The spatial experimental unit was the vertical monitoring profile. The spatial sample size was therefore one profile for the microtopographic configuration and one profile for the flat configuration ($n = 1$ $n = 1$ $n = 1$ per configuration). No bounded, replicated treatment plots were established. The reported 10.78 ha represents the total area across which the integrated restoration intervention was implemented and does not represent the dimensions of a replicated experimental plot. Because the measurements were collected at two point profiles, within-configuration spatial variability and the spatial representativeness of each profile could not be quantified.

2.5. Sensor Calibration and Measurement Uncertainty

The sensors were operated using the manufacturer's standard calibration. A substrate-specific laboratory calibration against gravimetrically measured volumetric water content was not conducted before field installation. Because dielectric soil-moisture measurements may be affected by bulk density, coarse-fragment content, soil texture, temperature, electrical conductivity, and probe–substrate contact, the measurements are described as sensor-derived apparent volumetric water content. Interpretation therefore emphasizes temporal patterns and relative differences between the monitored profiles rather than unqualified absolute soil-water values. Possible differences in substrate properties and electrical conductivity between the monitoring locations may also introduce systematic uncertainty into the profile comparison.

2.6. Data Processing and Descriptive Analysis

The synchronized 10 min records were screened for missing values, instrument error codes, physically impossible values, and isolated abrupt observations inconsistent with the immediately preceding and subsequent records. Daily medians and interquartile ranges were calculated to summarize temporal patterns and reduce the visual influence of high-frequency short-term fluctuations. Annual mean, standard deviation, minimum, maximum, median, and interquartile range were calculated separately for each monitoring profile and depth.

The relative profile difference at depth d was calculated as:

$$RDd = G \frac{\theta_{M,d}^- \theta_{F,d}^-}{\theta_{F,d}^-} \times 100$$

where RDd is the relative soil-moisture difference at depth d , $\theta_{M,d}^-$ is the annual mean apparent volumetric water content in the microtopographic profile, and $\theta_{F,d}^-$ is the corresponding annual mean in the flat profile.

Event responses were summarized using the 24 h pre-event median, maximum apparent water content, absolute event-related increase, time to peak, and the proportion of the event-related increase remaining after 72 h. The temporal sample size was 41,475 synchronized timestamps per profile, equivalent to 207,375 depth-specific observations per profile. The spatial sample size, however, was one monitoring profile per reclamation configuration. Given the absence of true spatial replicates, the large number of temporal measurements (41,475 points) cannot justify inferential statistical testing. Our comparisons between treatments are therefore descriptive, and the results should be viewed as exploratory rather than confirmatory.

Because no independent spatial replicates were available, no treatment-level t -test, analysis of variance, repeated-measures treatment test, or mixed-effects treatment model was performed. Treating the 10 min timestamps as independent replicates would have constituted temporal pseudoreplication and would have substantially overstated the cer-

tainty of the profile difference. Similarly, a confidence interval calculated directly from all timestamps would describe the precision of the temporal mean under the observed record rather than uncertainty among independently replicated reclamation plots.

Annual mean, standard deviation, minimum, maximum, median, and interquartile range were therefore used to characterize temporal variation within each profile and depth. Daily medians and interquartile ranges were used in time-series figures to reduce the influence of high-frequency noise. These statistics should not be interpreted as measures of spatial variability or evidence of a general treatment effect. Analyses were conducted using Python 3.12 with the pandas and NumPy libraries.

3. Results

3.1. Soil Moisture Changes in Different Soil Layers Between the Micro-Terrain Construction Area and the Flat Control Area

To evaluate the effects of micro-terrain modification on subsurface water redistribution, this section compares the soil moisture dynamics observed in the constructed area with those in the adjacent flat control plot across multiple depths and rainfall events. The analysis considers both seasonal trends and event-scale responses, using continuous monitoring data collected across 2024. Figure 4a and Figure 4b present the continuous monitoring results of soil moisture ratio at the 0–10 cm and 20–30 cm depths, respectively. Figure 5 provides a summary of the annual moisture enrichment rates across five soil layers (0–10, 10–20, 20–30, 30–40, and 40–50 cm), illustrating the varying intensity of water replenishment at different depths. Figure 6 shows the changes in surface soil moisture (0–10 cm) in both the micro-terrain constructed area and the flat control area after five successive rainfall events (labeled a–e), and offers qualitative explanations for the observed differences in moisture response, based on the underlying hydrological processes—some of which are derived from our field experimental experience. During the 2024 observation period, the two monitored profiles showed broadly synchronous seasonal fluctuations in soil moisture; however, their absolute moisture contents consistently differed across several depths and seasons, suggesting that micro-terrain modification has a persistent and depth-dependent effect on soil water distribution. The following subsections analyze in detail the soil moisture variations across layers and rainfall events, and their hydrological interpretations, for both the micro-terrain and flat plots.

3.1.1. Soil Moisture Dynamics at 0–10 cm Depth

Figure 4a presents the time series of soil moisture content at 0–10 cm depth for both the micro-terrain construction area and the flat control area, based on 40,320 monitoring nodes recorded at 10 min intervals from 1 January to 31 December 2024. The two curves exhibit a pronounced synchronization pattern throughout the year, characterized by nearly simultaneous rises and declines in soil moisture. This resonance phenomenon indicates that external climatic drivers—such as precipitation events, snowmelt pulses, and evaporation cycles—exert similar temporal controls on surface soil moisture regardless of terrain treatment. Despite this synchronous behavior, a consistent and persistent difference in magnitude is evident: the micro-terrain area maintains systematically higher soil water content compared to the flat control across almost the entire monitoring period. Several sharp, transient peaks exceeding 30% volumetric water content are observable in both treatments, with the micro-terrain area often showing slightly elevated peak values. These extreme moisture events correspond to specific meteorological episodes: one peak aligns with early April snowmelt, while three additional spikes coincide with heavy rainstorm events. The rapid rise and subsequent decline demonstrate a strong short-term response of the surface layer to episodic water inputs. The decline may reflect a combination of drainage, redistribution,

soil evaporation, plant uptake, and sensor-temperature effects, which cannot be separated using the present measurements. During several dry intervals between moisture pulses, the monitored microtopographic profile maintained higher sensor-derived water content than the flat profile. This persistent difference is consistent with prolonged near-surface water availability but may also reflect differences in substrate properties, vegetation, probe environment, or other site characteristics that were not independently controlled.

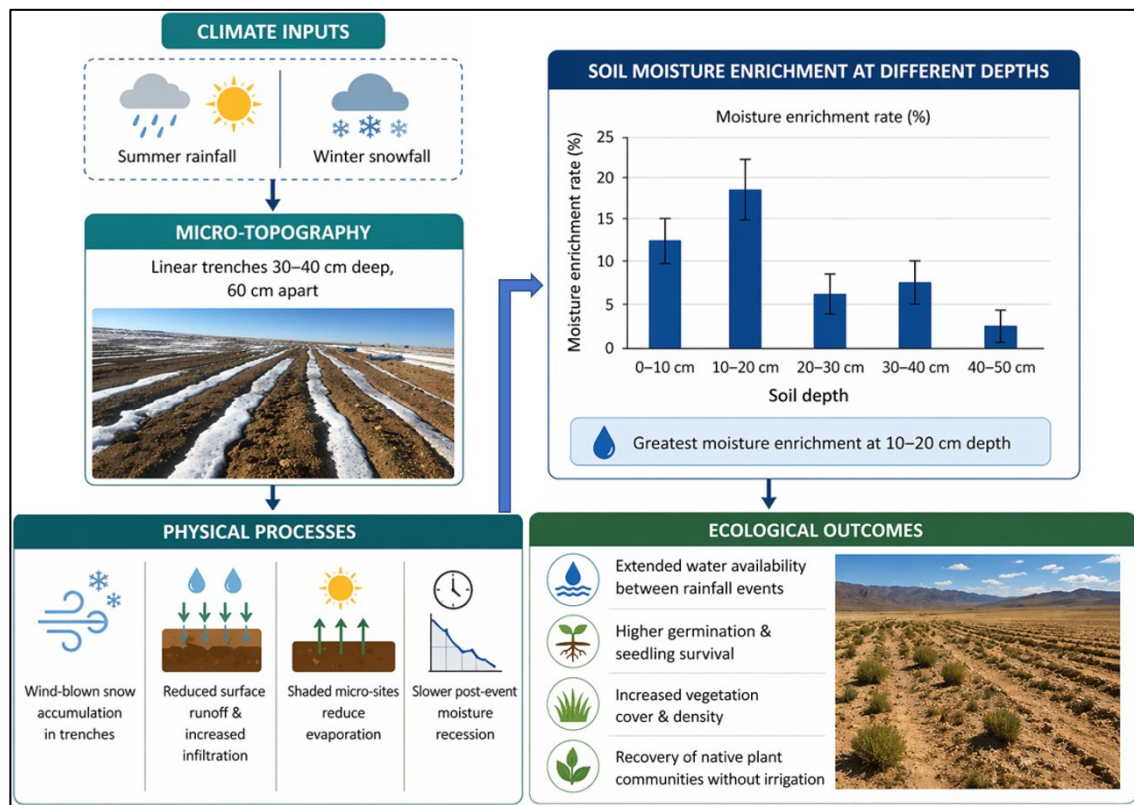


Figure 5. Annual relative difference in apparent volumetric water content between the monitored microtopographic and flat profiles across five depth intervals. Error bars show temporal variability within the monitoring record and do not represent variability among spatial replicates. Runoff, infiltration, evaporation, snow redistribution, and vegetation responses were not measured directly.

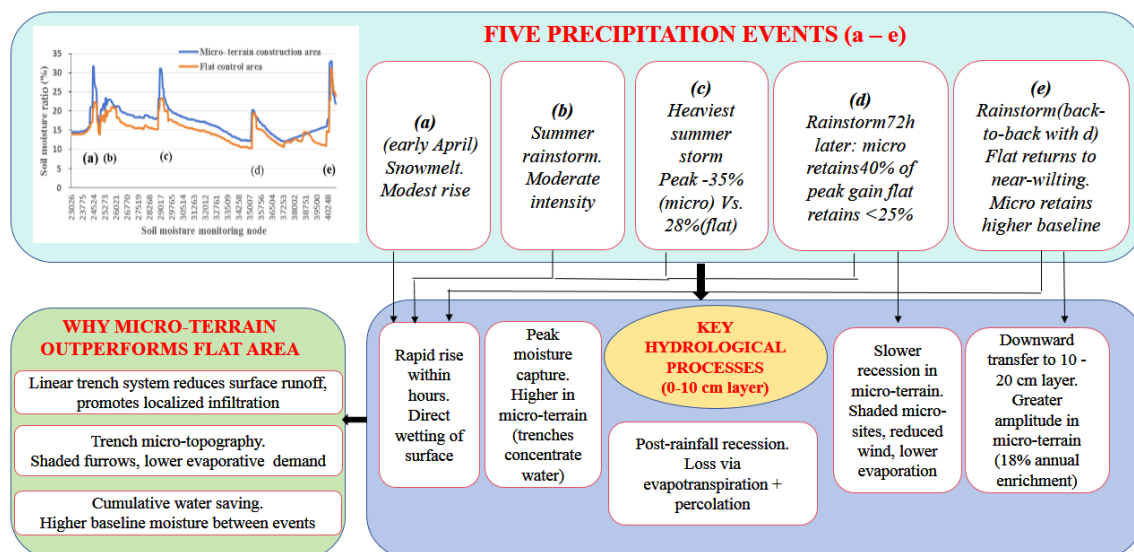


Figure 6. Variation in soil moisture in micro-terrain and flat area after rainfall in the 0–10 cm soil layer.

3.1.2. Soil Moisture Dynamics at 20–30 cm Depth

Figure 4b illustrates the soil moisture dynamics at 20–30 cm depth over the same annual cycle. Compared to the 0–10 cm layer, the overall temporal pattern at this depth is markedly dampened, with reduced amplitude of fluctuation and fewer sharp spikes. However, the synchronization between the micro-terrain and flat control areas remains evident, indicating that external moisture inputs still propagate to this intermediate depth, albeit with attenuated intensity. The micro-terrain area again exhibits consistently higher soil moisture than the flat control throughout most of the year. A particularly noteworthy feature is the differential response to the same extreme events identified at the surface. During the early April wetting period, the 20–30 cm record showed a broader and more gradual response than the 0–10 cm record. Similar dampened responses occurred during the selected summer events. These depth-dependent temporal patterns are consistent with delayed subsurface wetting but do not directly quantify infiltration or vertical flow. During several subsequent dry intervals, the monitored microtopographic profile retained a higher apparent water-content baseline than the flat profile. The persistent difference indicates that the two monitored profiles differed in subsurface wetting and drying behavior. Because runoff, infiltration rate, evaporation, and soil-water potential were not measured, the relative contributions of water concentration, downward redistribution, plant uptake, and evaporative loss cannot be separated from the soil-moisture record alone.

3.1.3. Annual Relative Profile Difference Across Soil Depths

Figure 5 quantifies the moisture enrichment effect—defined as the percentage increase in mean annual soil moisture in the micro-terrain area relative to the flat control area—across all five measured depth intervals. The enrichment rate exhibits a clear vertical stratification rather than a monotonic decline with depth. The maximum enhancement occurs at 10–20 cm depth, where soil moisture increased by approximately 18% over the full monitoring period. The 0–10 cm layer shows a substantial but slightly lower enrichment of 11.7%. At depths below 20 cm, enrichment rates diminish considerably: 5.5% at 20–30 cm, 6.1% at 30–40 cm, and only 1.9% at 40–50 cm. This depth-specific pattern demonstrates that the magnitude of the profile-level difference varied vertically, but it does not by itself identify the hydrological processes responsible for that variation.

The relative difference was greatest at 10–20 cm and lower at both the surface and the deeper measurement intervals. The smaller relative difference at 0–10 cm may be associated with the greater temporal variability and stronger atmospheric exposure of the surface layer. The reduced differences below 20 cm indicate that the detectable treatment-associated wetting signal was concentrated mainly in the upper profile during 2024. However, the pattern does not demonstrate that shallow storage was optimal or that deeper percolation represented a water loss. Restricted deeper wetting could also reflect limited precipitation input, reconstructed-substrate texture, compaction, hydraulic conductivity, root uptake, or water movement below the 50 cm monitoring limit. Accordingly, these depth patterns are interpreted as descriptive differences in monitored water content rather than direct evidence of a particular infiltration or evaporation mechanism.

3.2. Effect of Rainfall on Surface Soil (0–10 cm) Moisture Content

To further investigate how rainfall events influence the uppermost soil layer, we extracted five representative rainfall episodes (labeled a, b, c, d, and e) from the continuous 0–10 cm soil moisture record shown in Figure 3. These five events correspond to the most prominent moisture spikes observed during 2024, each triggered by a distinct precipitation input. Event a occurred in early April and was primarily driven by rapid snowmelt rather than liquid rainfall, while events b, c, d, and e were summer rainstorms of varying intensity

and duration. Figure 6 presents the detailed soil moisture response during these five events for both the micro-terrain construction area and the flat control area, allowing a direct comparison of their surface hydrological behavior.

For all five events, a consistent pattern emerges immediately after the onset of rainfall (or snowmelt): soil moisture at 0–10 cm depth rises sharply within the first few hours. This rapid increase reflects the direct wetting of the surface layer by incoming water before any substantial percolation or lateral redistribution occurs. The peak moisture content reached during each event is notably higher in the micro-terrain area than in the flat control. For instance, during the heaviest summer rainstorm (event c), the micro-terrain area attained nearly 35% volumetric water content, whereas the flat control peaked at approximately 28%. This difference indicates a larger event-related wetting response at the monitored microtopographic profile. The pattern is consistent with localized concentration of precipitation, but surface runoff and infiltration were not measured directly.

Following the peak, a post-rainfall recession phase begins. Apparent soil-water content in the 0–10 cm layer declined progressively after each peak. The measured decline represents the combined effects of drainage, redistribution, soil evaporation, plant water uptake, and possible temperature-related sensor response; these components were not quantified separately. The recession rate is initially steep—especially within the first 24–48 h after the event—and then gradually flattens as the surface layer approaches a drier baseline. Importantly, the micro-terrain area exhibits a slower recession compared to the flat control. For example, 72 h after the peak of event d, the micro-terrain area retained about 40% of its peak moisture increase, while the flat control retained less than 25%. The slower recession indicates prolonged event-related wetness at the monitored microtopographic profile. Potential explanations include localized water concentration, differences in surface exposure, substrate properties, vegetation, infiltration, and evaporation. Because these processes were not measured independently, their relative contributions cannot be determined.

The 0–10 cm record generally showed sharper and shorter-lived event responses, whereas the 10–20 cm record showed broader and more delayed changes. The relative difference at 10–20 cm was also the largest of the five monitored depths. These observations are consistent with depth-dependent redistribution and retention but do not directly demonstrate greater infiltration or reduced surface loss.

During closely spaced events, the monitored microtopographic profile maintained a higher apparent water-content baseline than the flat profile. This pattern indicates temporal persistence of the profile-level difference. Its potential importance for vegetation establishment remains hypothetical because germination, plant water status, survival, and root activity were not measured during 2024 (Figure 5).

3.3. Effect of Spring Snowmelt on Soil Water Increase in Different Layers of the Micro-Terrain Area

To evaluate how spring snowmelt influences soil water replenishment across different depths, we analyzed the temporal variation in soil water content within the micro-terrain treatment area from 1 March to 31 May 2024. Figure 7 presents the water enrichment rate (increase relative to pre-melt baseline) for five soil layers (0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–50 cm) over this 92-day period. The *x*-axis in Figure 7, labeled “Soil Moisture Monitoring Node 1–3829”, corresponds to the sequential measurements taken at 10-min intervals from 1 March through 31 May 2024, capturing the entire spring snowmelt season.

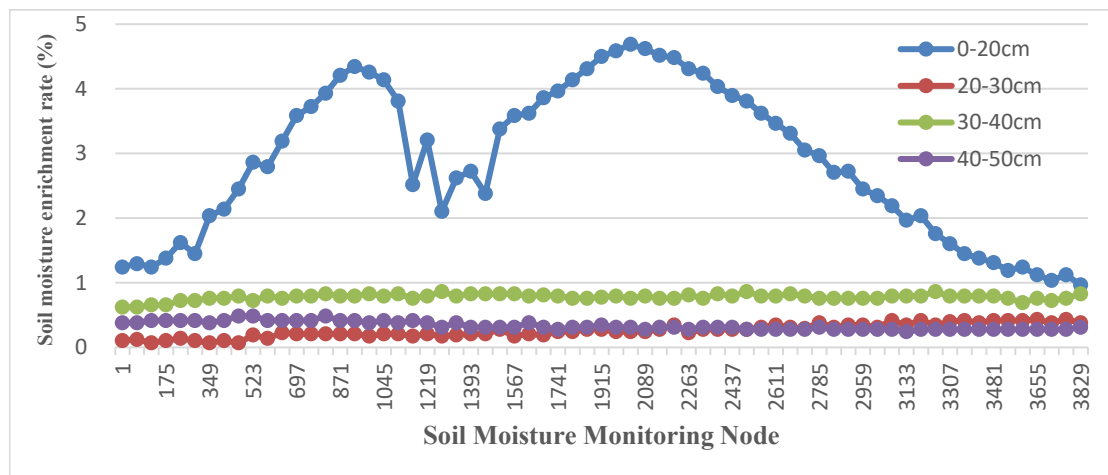


Figure 7. Water enrichment rate in different soil layers resulting from snowmelt.

A distinct depth-dependent pattern occurred during the March–May period. The relative difference was largest in the combined 0–20 cm interval and smaller in the monitored layers below 20 cm. This pattern indicates that the most pronounced detectable wetting response occurred in the upper profile. It does not, however, establish that snow was preferentially accumulated in the trenches because snow depth and snow-water equivalent were not measured. Similarly, the small response below 20 cm cannot determine whether water failed to infiltrate more deeply, moved below the 50 cm monitoring depth, or was affected by substrate hydraulic properties and root water uptake. It should be noted, however, that surface runoff and infiltration rates were not directly measured in this study. The interpretations regarding reduced runoff, enhanced infiltration, and lower evaporative losses within trenches are therefore inferred indirectly from soil moisture time-series patterns, rather than being supported by direct hydrological measurements.

A notable temporal trend was observed as the season progressed toward late May. The water enrichment rate in the 0–20 cm layer, although still higher than in deeper layers, gradually declined and approached the values of the 20–50 cm layers by the end of May. The convergence toward late May coincided with the end of the probable snowmelt period and increasing seasonal air temperatures. However, because snowmelt input, evapotranspiration, drainage, and root water uptake were not measured separately, the cause of the decline cannot be partitioned from the soil-moisture records alone. We acknowledge that snow depth and snow water equivalent were neither measured directly nor derived from volumetric soil moisture data in this study. Additionally, soil temperature and sensor performance during winter freeze–thaw cycles were not systematically monitored. Consequently, the reported snowmelt enrichment patterns are based solely on soil moisture responses, and the role of trench snow accumulation in these dynamics remains an inference rather than a directly confirmed mechanism.

4. Discussion

4.1. Depth-Dependent Soil-Moisture Differences and Possible Hydrological Explanations

The monitored microtopographic profile maintained higher sensor-derived soil-water content than the flat profile during much of 2024, with the largest relative difference at 10–20 cm. This depth-dependent pattern indicates that the strongest detectable difference occurred below the most atmospherically exposed surface layer but above the deeper part of the monitored profile. Similar upper-profile moisture responses have been reported for micro-catchment and terrain-modification systems in other dryland environments [16,19–21]. Direct numerical comparison should nevertheless be made cau-

tiously because those studies differ in substrate texture, precipitation regime, vegetation, irrigation, trench geometry, and monitoring design. Recent studies reinforce the importance of separating mining effects, vegetation effects, topographic effects, and temporal variability when interpreting soil-water differences. Continuous and remote-sensing investigations in semi-arid coal-mining landscapes have shown that mining disturbance can alter both mean soil moisture and its spatial variability. Long-term Loess Plateau monitoring has also demonstrated that soil-water responses depend jointly on revegetation type, topographic position, and precipitation magnitude. These findings support the cautious interpretation adopted here: the observed differences between the two existing profiles cannot be attributed solely to trench geometry. While the observed moisture enrichment is ecologically meaningful, it should not be equated with restoration success. Direct measurements of vegetation cover, biomass, seedling survival, or species diversity were not obtained in this study. Therefore, the increased soil moisture should be interpreted as a necessary but not sufficient condition for passive restoration, rather than as direct evidence of ecological recovery.

Several processes could contribute to the observed pattern. Constructed depressions may concentrate rainfall or redistributed snow, increase depression storage, alter surface roughness, and extend the time available for infiltration [39,40]. Trenches may also modify radiation, wind exposure, and evaporative conditions at the microsite scale. However, runoff, infiltration rate, snow depth, snow-water equivalent, soil-surface temperature, wind speed, evaporation, and matric potential were not measured in the present study. These processes should therefore be regarded as plausible explanations rather than demonstrated mechanisms. Differences in reconstructed-substrate properties, vegetation cover, root activity, and the local probe environment may also have contributed [41].

Throughout the following discussion, the hydrological mechanisms invoked—such as reduced runoff, enhanced infiltration, and lowered evaporative losses—are proposed as plausible explanations for the observed soil moisture patterns, rather than as empirically demonstrated processes. Given the absence of direct flux measurements, these interpretations should be viewed as working hypotheses that require independent verification in future studies. The limited relative difference below 20 cm does not necessarily demonstrate efficient retention in an optimal shallow root zone. It indicates only that the detectable water-content response was weaker at the monitored deeper layers [42,43]. This may reflect small water inputs, limited hydraulic conductivity, compaction, coarse-fragment distribution, preferential flow, root water uptake, or movement below the 50 cm monitoring depth. In arid environments, deeper infiltration can be ecologically valuable because it may reduce exposure to surface evaporation and provide water to deep-rooted perennial species. Consequently, the present results should not be interpreted as evidence that shallow storage is universally preferable to deeper infiltration.

Groundwater deeper than 200 m is unlikely to contribute directly to water content in the monitored 0–50 cm profile. Nevertheless, water may redistribute within the unsaturated profile in response to matric-potential gradients. Because soil-water potential was not measured, the direction and magnitude of such redistribution cannot be quantified (Figure 8).

Runoff-harvesting studies from the Negev Desert remain useful as conceptual examples of how surface configuration can redistribute limited water inputs. However, the Negev and Kalamaili systems are not directly equivalent. The Negev is influenced mainly by rainfall-generated runoff, whereas the Kalamaili site has a cold continental climate in which snowfall, wind redistribution, frozen-soil conditions, and spring melt may be important. The Negev precipitation threshold should therefore not be used as a

direct benchmark for this site. Comparative interpretation should instead emphasize the contrasting precipitation forms and seasonal hydrological processes.

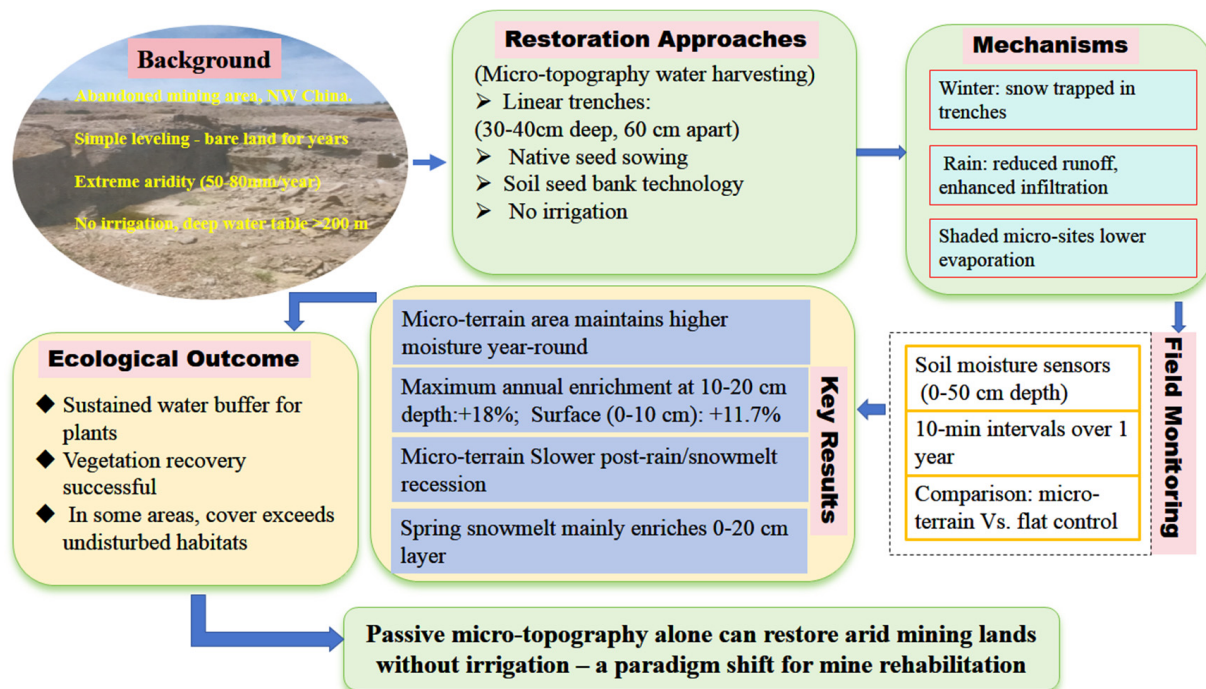


Figure 8. Scope of the observations and interpretations in the present case study. Solid boxes represent measured soil-moisture variables, whereas dashed boxes identify hydrological processes and vegetation responses that were not measured directly.

4.2. Event-Scale Wetting and Drying Responses

The selected moisture events showed larger peaks and slower post-event recession at the monitored microtopographic profile than at the flat profile. These observations indicate that event-related wetness persisted longer at the monitored microtopographic location. In a water-limited environment, a longer period of near-surface water availability could potentially extend the time available for seed germination and early root activity [44,45].

Nevertheless, the recession of sensor-derived water content represents the combined effects of drainage, redistribution, soil evaporation, plant water uptake, and temperature-dependent sensor response. The present dataset cannot partition these processes. Similarly, the response attributed to spring snowmelt was identified from the timing of the moisture increase rather than from direct measurements of snow depth or snow-water equivalent. Therefore, the event analysis supports a difference in wetting and drying behavior between the monitored profiles but does not independently quantify snow capture, runoff reduction, infiltration enhancement, or evaporation suppression.

Nevertheless, the proposed mechanisms—reduced runoff, enhanced infiltration, and suppressed evaporation—remain inferential, as none of these hydrological fluxes were directly measured in the field. The evidential value of these explanations is therefore constrained, and they should be viewed as hypotheses derived from soil moisture patterns rather than empirically validated processes. The ecological relevance of the observed moisture persistence also remains to be tested directly. Plant water potential, photosynthesis, root biomass, germination, seedling survival, and species-specific water use were not measured [46–48]. The event-scale patterns should therefore be viewed as potential hydrological benefits requiring plant-level validation rather than direct evidence of restoration success.

4.3. Implications for Mine-Land Revegetation and Treatment Confounding

Qualitative field photographs suggest visible differences in vegetation development between the integrated restoration area and adjacent leveled areas. Because vegetation cover, biomass, survival, and species richness were not measured systematically, these visual differences cannot be used as quantitative evidence of restoration performance. However, the restoration treatment combined trench construction, native seed sowing, transferred seed-bank topsoil, and water-retaining material [49]. These components address different establishment constraints: trenches may influence water redistribution, seed sowing supplies propagules, transferred topsoil introduces seeds, microorganisms, nutrients, and fine material, and water-retaining material may alter local water storage. Because these measures were not evaluated factorially, the independent effect of microtopography cannot be isolated.

Recent restoration studies also show that hydrological improvement alone does not establish ecological success. Plant survival in semi-arid mining reclamation may depend on species diversity, soil conditions, and stand development [50], while dryland restoration outcomes can vary strongly with substrate texture and the duration of water availability [51]. Direct vegetation measurements are therefore necessary before the observed soil-moisture differences can be translated into claims regarding plant survival, community development, or ecosystem recovery.

Monitoring also began several years after the restoration intervention. By 2024, vegetation roots, litter accumulation, localized organic-matter inputs, shading, and biological soil modification may already have altered infiltration, evaporation, and water uptake [52,53]. Consequently, the measured soil-moisture differences represent the current condition of two contrasting post-establishment areas rather than the direct, unmodified hydrological effect of trench construction in 2018.

The present observations nevertheless provide a basis for developing stronger future experiments. A factorial design comparing flat and trenched surfaces with and without seed-bank topsoil, seed sowing, and water-retaining material would allow the individual and interactive contributions of each treatment component to be quantified. Such experiments should include replicated plots, common substrate conditions, direct hydrological measurements, and species-specific vegetation responses.

The results should not yet be used to recommend mandatory microtopographic designs for all arid mine-reclamation projects. Performance may differ with climate, precipitation form, substrate texture, salinity, quarry material, slope, plant functional type, and construction geometry. Multi-site validation is required before general engineering or policy recommendations can be made. We also acknowledge that snow hydrological processes—including snow depth, snow water equivalent, and meltwater partitioning—were not directly investigated. Moreover, uncertainties related to winter sensor measurements, such as potential frost effects and soil temperature variability, were not fully resolved. Consequently, the interpretation of snow accumulation and meltwater contribution to trench moisture remains partly speculative and requires further validation through dedicated winter monitoring.

4.4. Limitations, Uncertainty, and Future Research

Several limitations constrain the interpretation and transferability of this case study. First, the monitoring record covers only one calendar year [53,54]. Precipitation and snowfall vary strongly among years in cold-arid environments, and the 2024 pattern may not represent multi-year droughts, unusually snowy winters, or extreme summer storms. Multi-year monitoring is therefore required.

Second, the high temporal resolution does not compensate for limited spatial replication. The 10 min observations are repeated measurements from the same sensor locations and are not independent treatment replicates. With independent monitoring profiles per area, the results cannot quantify spatial heterogeneity across the complete 10.78-ha restoration area. Additional replicated profiles should be distributed across representative trench positions, slope classes, substrate conditions, and vegetation states [55–57].

Third, the sensors were not calibrated specifically for the reconstructed quarry substrate. Their dielectric response may have been influenced by bulk density, coarse fragments, temperature, electrical conductivity, and probe–substrate contact. Consequently, uncertainty remains in both the absolute apparent water-content values and the magnitude of the difference between the two profiles. Dielectric-sensor readings may be affected by bulk density, coarse-fragment content, temperature, and electrical conductivity. Future monitoring should combine site-specific calibration with repeated gravimetric verification [58–60].

Fourth, monitoring began several years after restoration and after vegetation had become established. The 2024 soil-moisture dynamics cannot reconstruct the hydrological conditions responsible for germination and early succession during 2018–2020. Vegetation development and root-induced changes may themselves have affected the measured water dynamics.

Fifth, trenching, seed sowing, transferred seed-bank topsoil, and water-retaining material were applied together. Their independent contributions cannot be isolated. A replicated factorial experiment is needed to distinguish their individual and interactive effects.

Sixth, runoff, infiltration rate, drainage, evaporation, matric potential, snow depth, snow-water equivalent, surface roughness, soil-surface temperature, and near-surface wind speed were not measured. Therefore, the mechanisms underlying the observed water-content differences remain inferential. Future studies should combine replicated moisture profiles with runoff plots, infiltration tests, tensiometers, lysimeters or water-balance measurements, snow surveys, surface-energy observations, and repeated TDR surveys.

Seventh, monitoring was restricted to 0–50 cm. Water movement below 50 cm and its potential availability to deep-rooted perennial plants remain unknown. Future studies should extend measurements to at least 100 cm and use stable isotopes or other tracers to identify rainfall, snowmelt, soil-water, and plant-water relationships.

Eighth, direct vegetation responses were not quantified. Measurements of germination, survival, cover, species composition, biomass, rooting depth, plant water potential, stomatal conductance, and photosynthetic activity are required before increased soil moisture can be interpreted as improved ecological restoration. While soil moisture enrichment is a necessary precondition for vegetation recovery in hyper-arid environments, it is not a substitute for direct ecological endpoints. The absence of concurrent measurements of vegetation cover, biomass production, seedling establishment rates, or species diversity in this study means that soil moisture should be regarded as an early-stage physical indicator rather than a definitive measure of reclamation success.

Finally, the 30–40 cm depth and 60 cm spacing were empirically selected. The study did not test alternative geometries or quantify trench contributing area, depression-storage capacity, sediment accumulation, snow-storage capacity, structural degradation, maintenance requirements, construction cost, or long-term performance. Future factorial experiments and hydrological modeling should examine alternative trench widths, depths, spacing, orientation, and slope positions and evaluate their economic feasibility.

5. Conclusions

This one-year post-establishment case study identified persistent differences in sensor-derived apparent soil-water content between monitored microtopographic and flat reclama-

tion profiles at a cold-arid abandoned quarry. The largest annual relative profile difference occurred at 10–20 cm, followed by 0–10 cm, whereas differences were smaller below 20 cm. The monitored microtopographic profile also showed larger wetting responses and slower recession during selected rainfall and probable snowmelt periods.

These findings demonstrate contrasting soil-moisture dynamics between the two monitored reclamation configurations but do not establish the independent effect of trenching. The intervention combined microtopography, native seed sowing, transferred seed-bank topsoil and litter, and water-retaining material. Monitoring began several years after vegetation establishment; only one profile represented each configuration, and runoff, infiltration, evaporation, snow accumulation, deeper drainage, and plant responses were not measured directly.

The principal contribution of the study is therefore the high-frequency characterization of vertical and event-scale soil-moisture differences at two existing reclamation profiles. The results provide site-specific evidence for further evaluation of integrated micro-catchment reclamation designs but should not be interpreted as proof of an optimized or universally applicable restoration method. It is important to emphasize that these conclusions regarding ecological restoration potential are drawn from soil moisture evidence rather than direct measurements of vegetation recovery, species establishment, or ecosystem function. Given the methodological constraints—including the absence of spatial replicates and the single-year monitoring period—broad generalizations of the findings to other regions or climatic conditions are not warranted without further validation.

Author Contributions: Conceptualization, A.A.; methodology, A.A., H.X. and A.W.; formal analysis, F.B. and Y.Y.; writing—original draft preparation, A.A.; supervision, H.X. and A.W. All authors have read and agreed to the published version of the manuscript.

Funding: This study was jointly supported by the Ministry-Province Cooperative Project under the Ministry of Natural Resources (2024ZRBSHZ098) and “Water Effects and Recovery Mechanisms of Micro-Topography Construction Technology” (2025BSCK-04).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data may be provided on reasonable request from the first author.

Conflicts of Interest: The authors declare no conflicts of interest.

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